1-1-2006

Winter cereal grain - forage legume intercrops: component yield tradeoffs and potential for cultivar improvement

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Winter cereal grain – forage legume intercrops: Component yield tradeoffs and potential for cultivar improvement

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Sustainable Agriculture

Program of Study Committee:
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Iowa State University

Ames, Iowa

2006

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ABSTRACT

Single-year intercrops of winter cereal grains and forage legumes have an important contribution to make to North Central USA cropping systems, and improvement of component yields through informed cultivar choice or cultivar improvement could increase profitability and ease farmer adoption. This study sought to characterize winter cereal grain genotypes associated with high or low yields of each intercrop component and to identify cereal grain traits of potential utility in breeding for intercrop performance. Twenty-five winter wheat (*Triticum aestivum* L.) and 17 winter triticale (X *Triticosecale* Wittmack) lines were intercropped with red clover (*Trifolium pratense* L.) and evaluated for cereal grain canopy characteristics (including light interception, leaf area index [LAI], and leaf angle distribution), cereal grain morphology and phenology (height, tiller density, and heading date), and component yields (cereal grain yield and clover forage yield). Over two years, a tradeoff between grain yield and forage yield was observed in wheat ($r = -0.43$), but not in triticale. Wheat canopies with high light interception, high LAI, and highly horizontal leaves predicted not only low clover yield ($r = -0.53$, -0.59, and -0.54, respectively), but also high wheat yields ($r = 0.68$, 0.47, and 0.45, respectively). Triticale canopy characteristics displayed a less consistent pattern of relationship with component yields. Height was a predictor of low clover yields ($r = -0.50$) in triticale. Results did not clearly identify any cereal grain traits for potential use as criteria in indirect selection for component yields.

CHAPTER 1. GENERAL INTRODUCTION

Thesis Organization

The thesis is centered around a research report in journal article-format, comprising its second chapter. Co-major professors Dr. E. Charles Brummer and Dr. Jean-Luc Jannink are listed as coauthors of that report in recognition of their major contributions to the design, execution, and analysis of the research described therein. An introductory chapter expanding on the context in which the research was conceived and performed precedes Chapter 2, and a concluding chapter further discussing implications and possible avenues for further research follows.

Cereal Grain – Forage Legume Intercrops in the Cropping System

A variety of challenges exist to the sustainability and profitability of the corn *(Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] cropping system predominating in the North Central USA (Tilman, 1999) The ability of that system to maintain soil quality, effectively control pest and weed pressures, and provide adequate, stable income to farmers and other agricultural workers is increasingly being called into question (Brummer, 1998). Agroecological diversification is frequently proposed as a mechanism for increasing the capacity of a cropping system for endogenously-driven crop protection, conservation of environmental quality, and biophysical and economic stability. Two crop types with historically proven niches in the region's agricultural systems are cereal grains such as oat (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) and forage legumes like alfalfa (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.). Reintroduction of these crops holds promise for improvement of present-day cropping systems, but implementation will require an intentional approach.

The life histories of corn and soybean define temporal windows of vulnerability to soil erosion in the winter months when standing biomass is not present to provide ground cover. Through their presence on the landscape during the parts of the year when corn and soybean are absent, winter cereal grains and perennial or biennial forage legumes can bring the cropping system closer to continuous ground cover and reduce soil erosion (Kaspar et al., 2001). The extensive fibrous and deeply taprooted root architectures of the latter crop types may also decrease soil erodibility and increase crop rotation contributions to soil organic matter.

Spatial diversification produced at the landscape and farm scales by the inclusion of cereal grains and forage legumes in rotations may emplace important obstacles to the success of host-specific herbivorous insects and plant pathogens by decreasing resource concentration (Root, 1973) and thereby increasing the average time and energy expenditure involved in finding an appropriate target crop site. Temporal diversification of the crop rotation exposes pests and weeds to a wider array of environmental conditions and management tactics each of which they must negotiate in order to proliferate (Liebman and Dyck, 1993).

The nitrogen contribution of a forage legume stand to a following crop is often substantial. When the production of forage legumes also entails on-farm utilization by livestock, further opportunities arise for reducing fertility costs and optimizing mass flows through field application of animal manures and reduction of nutrient exports from the farm. These fertility contributions combine with pest and weed pressure reductions to lend crop rotations diversified with cereal grains and forage legumes the potential to increase corn and soybean yield and profitability (Crookston et al., 1997) and the profitability and stability of the cropping system as a whole (Brummer, 1998).

While the potential for medium- and long-term benefits is real, short-term disadvantages driven by the structure of the agricultural system challenge adoption by farmers. Federal crop subsidy programs for the North Central USA revolve around corn and soybean production, and significantly increase the profitability of those crops – and in the process create opportunity costs for decisions to forgo corn or soybean hectarage in favor of other crops (Ikerd 1996). Long-term trends towards corn and soybean specialization and concentrated livestock production have also increased the initial challenges and costs involved in the marketing or on-farm utilization of cereal grains and forages (Padgitt et al., 2000).

Historical crop rotations in the region frequently succeeded corn and soybean with one year of cereal grain production and a further one to three years of a continuous forage legume stand. While the agroecological benefits offered by such rotations are formidable, so also may appear to farmers the management and marketing challenges associated with devoting 50 to 66% of cropped hectares to non-corn, non-soybean crops. A single year cereal grain-forage legume intercrop could capture many of the benefits of a longer rotation including both crops by providing additional crop yields, exposing weeds and pests to new management environments, and contributing N to subsequent corn, while at the same time minimizing the number of hectares removed from corn or soybean production at any given time (Ghaffarzadeh, 1997). This strategy maximizes both compatibility with preexisting corn-soybean management practices and the number of hectares fully eligible for Federal commodity programs, and perhaps also the odds that farmers will decide to incorporate cereal grains and forage legumes into rotations.

While the ability of typical North Central cereal grain species like wheat, oat, and barley (*Hordeum vulgare* L.) to accommodate the successful establishment of undersown forage legumes intended for multi-year stands is well documented by farmers (Simmons et al., 1992) and researchers (e.g. Peters, 1960), single-year cereal grain-forage legume intercrops place a different demand on their legume component: the need for satisfactory establishment year yield. The substantial suppression of establishment year yields by cereal grain overstories, however, is nearly axiomatic in the literature (Peters, 1960, Pritchett and Nelson, 1951, Fukai and Trenbath, 1993). Improvement of first year forage legume yields, then, comprises one pathway through which agricultural research resources can be brought to bear on the crop diversification issue.

Efforts to mitigate suppression of first-year clover yield through informed cereal grain cultivar choice by farmers or through targeted cultivar improvement by plant breeders are logical steps toward a solution. Either approach requires the formulation of specific criteria distinguishing "better" cereal grain phenotypes from "worse" phenotypes. Both general ecological theory (Barbour, 1998) and experience with field crops (Vandermeer, 1989) suggest the possibility, however, that traits that reduce suppression of an understory crop by an overstory crop may not be associated with simultaneous high yields by the overstory crop. Research directed at identifying and characterizing those cereal grain cultivars that maximize or minimize component yields of a cereal grain-forage legume intercrop and elucidate the nature of any component yield tradeoffs that exist is therefore in order, and is the subject of this thesis.

References

Barbour, M.G, J.H. Burk, W.D. Pitts, M.W. Schwartz, and F. Gilliam. 1998. Terrestrial Plant Ecology, 3rd ed. Addison Wesley Longman, Menlo Park, CA.

Brummer, E.C. 1998. Diversity, stability, and sustainable American agriculture. Agron. J. 90:1-2.

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron J. 83:108-113.

Fukai, S., and B.R. Trenbath. 1993. Processes determining intercrop productivity and yields of component crops. Field Crops Res. 34:247-271.

Ghaffarzadeh, M. 1997. Economic and biological benefits of intercropping berseem clover with oat in corn-soybean-oat rotations. J. Prod. Agric. 10:314-319.

Ikerd, J.E. 1996. Government policy options: Implications for weed management. J. Prod. Agric. 9: 491-495.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. Appl. 3:92-122.

Kaspar, T.C., J.K. Radke, and J.M. Laflen. 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56:160-164.

Padgitt, M., D. Newton, R. Penn, and C. Sandretto. 2000. Production practices for major crops in U.S. agriculture, 1990-97. [Online]. Available at http://www.ers.usda.gov/Publications/sb969/ (Accessed 4 Jan. 2006; verified 31 Jan. 2006). USDA-Economic Res. Serv. Statistical Bull. No. 969.

Peters, R.A. 1960. Legume establishment as related to the presence or absence of an oat companion crop. Agron J. 52:195-198.

Pritchett, W.L. and L.B. Nelson. 1951. The effect of light intensity on the growth characteristics of alfalfa and bromegrass. Agron. J. 43:172-177.

Root, R.B. 1973. Organization of a plant-arthropod association in simple and diverse habitats: The fauna of collards (Brassica oleracea). Ecol. Monogr. 43:95-124.

Tilman, D. 1999. Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. Proc. Natl. Acad. Sci. 96:5995-6000.

Vandermeer, J. 1989. The Ecology of Intercropping. Cambridge Univ. Press, Cambridge, UK.

CHAPTER 2. WINTER CEREAL GRAIN – FORAGE LEGUME INTERCROPS: COMPONENT YIELD TRADEOFFS AND POTENTIAL FOR CULTIVAR IMPROVEMENT

A paper to be submitted to *Crop Science*

Frederick W. Iutzi, E. Charles Brummer, and Jean-Luc Jannink

Abstract

Single-year intercrops of winter cereal grains and forage legumes have an important contribution to make to North Central USA cropping systems, and improvement of component yields through informed cultivar choice or cultivar improvement could increase profitability and ease farmer adoption. This study sought to characterize winter cereal grain genotypes associated with high or low yields of each intercrop component and to identify cereal grain traits of potential utility in breeding for intercrop performance. Twenty-five winter wheat (*Triticum aestivum* L.) and 17 winter triticale (X *Triticosecale* Wittmack) lines were intercropped with red clover (*Trifolium pratense* L.) and evaluated for cereal grain canopy characteristics (including light interception, leaf area index [LAI], and leaf angle distribution), cereal grain morphology and phenology (height, tiller density, and heading date), and component yields (cereal grain yield and clover forage yield). Over two years, a tradeoff between grain yield and forage yield was observed in wheat (r = -0.43), but not in triticale. Wheat canopies with high light interception, high LAI, and highly horizontal leaves predicted not only low clover yield (r = -0.53, -0.59, and -0.54, respectively), but also high wheat yields (r = 0.68, 0.47, and 0.45, respectively). Triticale canopy characteristics displayed a less consistent pattern of relationship with component yields. Height was a predictor of low clover yields (r = -0.50) in triticale. Results did not clearly identify any cereal grain traits for potential use as criteria in indirect selection for component yields.

Introduction

Historically, cereal grains and forage legumes have played a major role in North Central USA cropping systems. When included in the corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation, these crops can help to increase diversity and stability, and mitigate soil, pest, and weed problems (Liebman and Dyck, 1993; Crookston et al., 1997; Brummer 1998). Despite these benefits, the low cash returns associated with cereal grains and forages relative to corn and soybean discourage their widespread adoption in the region. "Third year" intercropping of a cereal grain with an annual forage legume affords the opportunity to capture some of the ecological benefits of both crop types, while maximizing both compatibility with preexisting corn-soybean management practices and immediate cash returns (Ghaffarzadeh, 1997).

Cereal grains have a long history as nurse crops for establishment of multi-year forage legume stands. The desired outcome of their use is a well-established stand ready for second-year production (Peters, 1960; Simmons et al., 1992). Beyond successful forage legume establishment, however, employment of cereal grain-forage legume intercrops within the window of a single year places particular importance on achievement of a satisfactory establishment year forage yield. Significant depression of establishment year yields, however, is widely regarded as characteristic of such systems (Peters, 1960; Pritchett and Nelson, 1951; Fukai and Trenbath, 1993). Choice or improvement of cereal grain cultivars on the basis of expected compatibility with forage legume success are appropriate management and breeding responses. In order to achieve whole-system yield goals, however, decision criteria must also exclude the selection of cereal grain genotypes that are themselves low-yielding.

It is desirable in this context to acquire information on the effects of specific cereal grain cultivars on both grain and legume forage yield in intercrop settings, and to assess potential needs and avenues for cultivar improvement. Breeding approaches may involve direct selection for one or both component yields, or indirect selection for yield based on particular morphological or phenological characteristics via ideotype breeding (Donald, 1968) or the employment of selection indices (Lin, 1978). The latter approaches demand identification of specific traits that appear to be unassociated with yield tradeoffs between crops or that minimize the potential tradeoff between crops.

Competition for light is a key mode of interaction between crops of varying architectures in polyculture settings (Vandermeer, 1989), and modification of the light environment by a taller cereal grain crop is a major contributor to concurrent reduced forage legume performance (Fukai and Trenbath, 1993; Pritchett and Nelson, 1951). Mature cereal grain canopies can exceed 90% light interception (Campbell and van Evert, 1994; Klebesdal and Smith, 1960), challenging the photosynthetic demands of an understory crop. Light interception may simplistically be regarded as a function of the amount or density of foliage present and the architecture of that foliage, frequently represented by mean leaf area index (LAI) and mean leaf angle, respectively (Campbell and Norman, 1998). Varying evolutionary strategies for maximizing photosynthetic activity or neighbor-shading mean that crop species or biotypes exhibiting similar light interception in a given environment may be expected to differ in relative values of LAI and leaf angle (Hikosaka and Hirose, 1997; Duncan, 1971).

Other plant morphological traits have the ability to directly or indirectly influence the light environment as well. Gross differences in plant height establish overstory-understory relationships, while smaller height differences may interact with solar zenith angle to influence light penetration to the understory (Campbell and Norman, 1998; Sakai, 1991). Branching and tillering make other modifications to light environment parameters. Overall above ground biomass production corresponds to the size, density, and orientation of particular light-intercepting canopy structures in a variety of complex ways (Tremmel and Bazazz, 1993; 1995).

Differences in light interception and morphology can also operate over time (Keating and Carberry, 1993). Canopy architecture changes as schedules of vegetative growth, reproductive development, senescence, and crop removal operate, and the light environment may be modified accordingly. The phenological compatibility or lack thereof of intercrop components has important implications for the welfare of an understory crop (Fukai and Trenbath, 1993). In cereal grains, heading date is a phenological milestone of particular interest.

Flanagan and Waskho (1950) observed that higher light interception by oat (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) canopies suppressed red clover (*Trifolium pratense* L.) and alfalfa (*Medicago sativa* L.), and that light interception was itself associated with cereal grain tiller density and height. Collister and Cramer (1952) found that oat height was negatively correlated with red clover yield, but could not link it to oat yield. Dwarf oat and barley cultivars were observed by Nickel et al. (1990) to suppress an alfalfa intercrop to a lesser extent than did conventional stature cultivars. In a similar experiment, however, Simmons et al. (1995) did not find differences between statures in legume yield suppression. Holland and Brummer (1999) found no evidence for a correlation between oat height and berseem clover (*Trifolium alexandrium* L.) yield, but observed that later oat heading date predicted lower clover yields.

Research on light competition in cereal grain-forage legume systems for the North Central USA has focused primarily on the spring cereal grains. Beyond the benefits provided by spring cereal grains, however, fall-planted cereal grains such as winter wheat (*Triticum aestivum* L.) have higher yield potential, provide ground cover through the winter, reduce the risk associated with limited suitable days for fieldwork in the early spring, and through their substantial early season nitrogen uptake may help mitigate the loss of fertilizer nitrate from corn systems (Shipley et al., 1992; Coale et al., 2000). In addition to traditionally-employed winter wheat, another winter cereal grain option has relatively recently become known in the region. Winter triticale (X *Triticosecale* Wittmack) shares a similar life history with winter wheat, and the amino acid composition of triticale grain makes it particularly valuable as a swine feed (Bruckner et al., 1998), and the focus of increasing attention from farmers and researcher.

When a one to three-year stand is desired and end utilization requirements do not specifically demand alfalfa, red clover has historically been a common choice for intercropping applications in the region due to its ability to tolerate low light conditions (Gist and Mott, 1957). Brummer and Holland (2001) point out that in single-year intercropping systems, the need for mechanical or chemical termination in the following rotation year may be avoided through the choice of a non-dormant, highly winterkilling legume component, and suggest the high-yielding, Southern USA-adapted medium red clover cultivar 'Cherokee' for the purpose.

This study evaluated winter wheat and winter triticale cultivars and lines for grain yield, yield of underseeded red clover, light interception, and morphological and phenological characteristics relevant to light competition. Information sought included an assessment of the presence or absence of component yield tradeoffs in commonly used wheat and triticale cultivars in the region, identification of superior individual wheat and triticale cultivars on the basis of intercropping performance, and elucidation of the relative importance and interaction of specific cereal grain traits in predicting component yields.

Materials and Methods

Two field experiments respectively incorporating 25 winter wheat and 18 winter triticale genotypes were carried out during the 2001-2002 and 2002-2003 seasons near Ames, Iowa, USA (42° 00' N, 93° 50' W) on a Nicollet loam (fine-loamy, mixed, mesic Aquic Hapludolls). Wheat genotypes were commercially-available cultivars and University of Nebraska experimental breeding lines and were primarily hard red types, although soft red and hard white types were also present. Both released cultivars and University of Nebraska experimental breeding lines were also represented in the set of triticale genotypes used, as were both grain and forage architectures. Released cultivars discussed are a subset of those enumerated by Skrdla and Jannink (2002, 2003). All genotypes were planted at a rate of 101 kg ha^{-1} on 26 September 2001 and 23 September 2002. Plots measured 1.2 m by 2.4 m and comprised four 0.3 m-spaced rows, and entries of each species were replicated three times in separate randomized complete block designs. 'Cherokee' medium red clover was broadcast with a 1.2 m drop spreader (Gandy Co., Owatonna, MN, USA)[1] onto all plots on 25 February

[1] Mention of a brand name does not constitute an endorsement by the authors of this study.

2002 and 26 February 2003 at a rate of 22 kg ha^{-1} in a frost-seeding procedure. Plots were rolled immediately after planting in 2002 in an attempt to enhance seed-to-soil contact, but no rolling was performed in 2003.

Observations were made on a number of wheat and triticale morphological and phenological characteristics throughout the growing season, and both grain and clover forage yields were determined. With the exception of grain yield, all observations were made with respect to the center two rows of each four-row plot; Table 1 summarizes the schedule on which they were conducted.

Percent light interception of the cereal grain canopy was calculated through above- and below-canopy observations of photosynthetically-active radiation in each plot on two dates each year. A line quantum sensor (Sunfleck Ceptometer model, Decagon Devices, Pullman, WA, USA) with a 90 cm sensor array was used within one hour of local noon on cloud-free days, and below-canopy observations were recorded as the average of four observations in the center interrow space of each plot.

Cereal grain mean leaf area index (LAI) and mean leaf angle were estimated twice each year with a hemispherical gap fraction instrument (LAI-2000 model, LI-COR, Lincoln, NE, USA) (Welles and Norman, 1991). The instrument was configured so that the operator's shadow was masked, and was employed under overcast skies in one above- and three below-canopy observations in each plot; the latter were performed along a diagonal transect in the central interrow space as suggested in the manufacturer's literature. Leaf angle was recorded as the complement (90 – X) of the mean tilt angle statistic computed by the instrument; lower values therefore indicate more erect leaves. Welles and Norman (1991) point out that the parameters estimated by this method might better be described as "foliage area index" and foliage angle, since no attempt is made to exclude the effects of non-leaf structures.

Cereal grain heights were measured on four occasions each year, and were recorded as the average of the height of the tallest point on a wheat or triticale plant at three locations within each plot. Tiller density was calculated from tiller counts made in 0.25 m sections of row in two locations per plot is expressed as tillers per m of row. Heading dates were recorded as the number of days after 1 May at which 50% of spikes in a plot were observed to be fully exserted.

Wheat and triticale grain was harvested from the totality of each plot by small-plot combine and dried to equilibrium moisture. The harvester's head was operated at a height of approximately 30 cm, and loose straw was removed from the plots. Red clover forage yield was determined on a single date each year when approximately 50% of inflorescences were in bloom in all plots. Clover was hand harvested at ground level from two 0.25 m quadrats in the center interrow space of each plot. The clover samples were dried at 60°C for four days and their biomass recorded.

Statistical analyses for each experiment were performed using SAS 9.1. ANOVA statistics were calculated using PROC GLM under the model

$$Y_{ijk} = \mu + Y_i + B_{(i)j} + G_k + YG_{ik} + \varepsilon_{(i)jk}$$

where μ is the mean of all cereal grain genotypes, Y_i is the random effect of the *i*th year, $B_{(i)j}$ is the random effect of the *j*th block nested within the *i*th year, G_k is the fixed effect of the *k*th cereal grain genotype, YG_{ik} is the interaction effect associated with years and genotypes, and $\varepsilon_{(i)jk}$ represents the random error associated with each plot. F-test denominators were $B_{(i)j}$ for tests of Y_i, YG_{ik} for tests of G_k, and $\varepsilon_{(i)jk}$ for tests of all other effects. PROC CORR was employed to compute all pairwise Fisher z-transformed Pearson correlation coefficients between response variables based on genotype means across both years of the experiment. Fisher's LSD was calculated for grain and clover yields for winter wheat cultivars and winter triticale cultivars and lines. Significance was assessed at the 5% significance level unless otherwise stated.

Results and Discussion

Significant genotype by year interactions were present for April height in wheat, June LAI and heading date in triticale, and May heights and grain yield in both species (Table 2). Among those variables, the contribution of the g × e term to the overall variance relative to the contribution of genotype was substantial ($F \geq 5$) for April and early May height and grain yield in wheat, and June LAI in triticale. Visual inspection of means suggested that both magnitude- and rank-change interaction modes were present in those cases. Because g × e interactions were limited to a few variables, and because our primary tool for assessing cereal grain line performance is average response over time, the two years of the experiments remained grouped together for further analysis.

Simple statistics for response variable means in each experiment may be inspected in Table 3. Significant effects of genotype suggested that variability present in most of the cereal grain morphological, phenological, and yield traits of interest was affected by cereal grain genotype; exceptions were April height and grain yield in wheat, clover yield in triticale, and May LI in both species (Table 2). Interrelationships between response variables in both species are next used to elucidate relationships between traits.

Wheat grain yield was negatively correlated with clover yield (r = -0.43), although no definite association was seen in the triticale experiment (Table 4). This apparent intercrop component yield tradeoff is unsurprising, conforming to literature on those systems (e.g. Fukai and Trenbath, 1993; Pritchett and Nelson, 1951), and reveals no easy answers to the question of winter cereal grain cultivar choice for single-year intercrops. Within the set of cultivars studied, farmers may be best served by selection of cultivars based on the relative importances of grain and legume forage to their operations.

Light interception, LAI, and leaf angle of the cereal grain canopy were the best predictors of clover yields in both wheat and triticale (Table 4). In the wheat experiment, genotypes with higher light interception, LAI, and leaf angle (May only) were associated with lower clover yield for both the May and June sampling dates (respective r-values between those predictor variables and clover yield ranged from -0.46 to -0.59). Similar relationships were observed in triticale (r = -0.43 to -0.70), with the exception of that involving June LAI. Overall, the presence of a leafy, horizontal-leaved cereal grain canopy intercepting a high proportion of incident light tended to coincide with low clover yields.

Compared to clover yield, grain yield was predicted with similar strength but opposite sign. Light interception, LAI, and leaf angle in both May and June correlated to wheat grain yield with coefficients ranging from 0.45 to 0.68, although no evidence existed for a relationship with May leaf angle (Table 5). Moderately strong prediction of high triticale yield by the variables in question was observed (r = 0.37 to 0.65), but evidence was less consistent: only in the case of June light interception was it clearly statistically significant, while the p-values associated with the other five variable by sampling date pairs range from 0.06 to 0.12. High grain yields were generally predicted by wheat and triticale genotypes with leafy canopies, horizontal leaves, and the ability to intercept a high proportion of incident light. The coincidence of low grain yields with vertical leaf angle distributions is contrary to the suggestion of Hikosaka and Hirose (1997) that at low or moderate values of LAI (LAI < 5), the dependence of canopy photosynthesis (and presumably also of yield components) on leaf angle is likely to be small. Hikosaka and Hirose base their analysis on direct measurements of leaf angle, rather than the method of estimation via gap fraction instrumentation used here.

Little clear evidence was found for relationships between other proposed predictor variables and cereal grain or clover yield (Table 5). Other than the June observation in triticale (r = -0.50), no height variables correlated significantly with clover yield. This general result is inconsistent with the intuitive understanding of many agricultural practitioners of the relationship between overstory crop height and understory effects (Simmons et al. 1992) and with the results of Collister and Cramer (1952) and Nickel et al. (1990). Other authors, also working in spring cereal grains, have however similarly failed to observe an effect of height on forage legume yield (Holland and Brummer, 1999; Simmons et al., 1995). On the other hand, both May and June light interception were predicted by cereal grain height in June, May light interception was also correlated with April height, and triticale light interception with early and late May height, perhaps in some measure of concurrence with the survey respondents of Simmons et al. (1992).

Later triticale heading dates were moderately associated with low grain yield (r = -0.60, Table 5), which likely reflected poorer adaptation of later-maturing lines to the Iowa environment, but later heading had no observed relationship with clover yields, in contrast to the finding of Holland and Brummer (1999) in oat. Tiller density did not significantly predict either component yield in either cereal grain species. In wheat, higher tiller densities were associated with greater June light interception, and later heading dates coincided with higher light interception and LAI values in both May and June, and higher leaf angle in June (Table 5).

Leaf area index and leaf angle were strongly correlated with one another on each sampling date in each species, and LAI observations at the two dates were also strongly interrelated (Table 5). May and June leaf angle shared a significant but weaker relationship. The association between light interception and LAI was moderate to strong on each sampling date in each species, and moderate between light interception and leaf angle. Overall, the three variables appeared to contribute substantially the same information with respect to prediction of grain and clover yields. Conditions in May and June similarly did not seem to differ importantly from one another in predictive strength. For purposes of prediction of grain and legume forage yields in future studies, a single sampling date within the May to June period and the use of only one of the two light-sensing instruments employed here (a line quantum sensor, contributing the light interception variable, and a hemispherical gap fraction instrument, contributing the LAI and leaf angle variables) may reduce labor and equipment expenditures with a minimal sacrifice of useful information.

Conclusions

Overall, previously recognized competitive traits like high light interception and a horizontally-leaved canopy predicted, when present in the overstory cereal grains considered, low performance from the clover understory. At the same time, those traits frequently appeared to be important predictors of cereal grain success, revealing no obviously useful selection criteria for simultaneous improvement of both component yields. Ideotype or selection index development based solely on the set of traits usually associated with light competition may not be a profitable breeding approach in this context. Results from this study suggest that identifying cultivars that incrementally reduce the tradeoff between grain yield and clover yield will require measuring those yields directly.

Evaluation of a number of winter wheat and winter triticale cultivars and breeding lines suggested that light interception, LAI, and leaf angle of the cereal grain canopy were the most important of the morphological and phenological traits examined in predicting grain yield and the forage yield of interseeded red clover. Grain and clover yields were inversely related to one another and to values observed for the aforementioned traits. No specific cereal grain traits likely to reduce the tradeoff between intercrop component yields if used as selection criteria were revealed by the data. Farmers implementing intercrops of winter cereal grains and forage legumes as “third year” rotation crops may be best guided in choosing cereal grain cultivars by the relative economic values of the intercrop components, and extension efforts might profitably be turned towards aiding in that decision process. Breeding efforts geared towards improving intercropping performance may be better directed toward developing cereal grain ideotypes or selection indices based on alternative classes of traits such as those related to root assimilate uptake, or towards cultivar improvement in the forage legume component of the intercrop.

Acknowledgments

Financial support from The Land Institute Natural Systems Agriculture Fellows program and the Iowa State University (ISU) Raymond F. Baker Center for Plant Breeding is gratefully acknowledged. The authors also thank Dr. P. Stephen Baenziger, University of Nebraska-Lincoln Department of Agronomy and Horticulture, for supplying the triticale breeding lines used, and Dr. Kenneth Moore and Dr. Matthew Liebman, ISU Department of Agronomy, for the use of field apparatus.

References

Bruckner, P.L., S.D. Cash, and R.D. Lee. 1998. Nitrogen effects on triticale grain yield, amino acid composition, and feed nutritional quality for swine. J. Prod. Agric. 11:180-184.

Brummer, E.C. 1998. Diversity, stability, and sustainable American agriculture. Agron. J. 90:1-2.

Brummer, E.C. and J.B. Holland. 2001. Small grain and annual forage legume intercrops for Iowa. Competitive Grant Rep. 98-6. [Online]. Available at http://www.leopold.iastate.edu/research/grants/completed_grants.htm (Accessed 12 Dec. 2005; verified 31 Jan. 2006). Leopold Cent. Prog. Rep. 10.

Campbell, G.S. and F.K. van Evert. 1994. Light interception by plant canopies: efficiency and architecture. In J.L. Monteith, R.K. Scott, and M.H. Unsworth, Resource Capture by Crops. Nottingham Univ. Press, Nottingham.

Campbell, G.S. and J.M. Norman. 1998. An Introduction to Environmental Biophysics, 2nd ed. Springer-Verlag, New York.

Coale, F.J., J.M. Costa, G.A. Bollero, and S.P. Schlosnagle. 2001. Small grain winter cover crops for conservation of residual soil nitrogen in the mid-Atlantic Coastal Plain. Am. J. Alternative Agric.16:66-72.

Collister, E.H. and H.H. Kramer. 1952. The effect of oat variety on the stand and development of red clover. Agron. J. 44:385.

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron J. 83:108-113.

Donald, C.M. 1968. The breeding of crop ideotypes. Euphytica 17:385-403.

Duncan, W.G. 1971. Leaf angles, leaf area, and canopy photosynthesis. Crop Sci. 11:482-485.

Flanagan, T.R. and J.B. Washko. 1950. Spring grain characteristics which influence their value as companion crops. Agron. J. 42:460.

Fukai, S., and B.R. Trenbath. 1993. Processes determining intercrop productivity and yields of component crops. Field Crops Res. 34:247-271.

Ghaffarzadeh, M. 1997. Economic and biological benefits of intercropping berseem clover with oat in corn-soybean-oat rotations. J. Prod. Agric. 10:314-319.

Gist, G.R. and G.O. Mott. 1957. Some effects of light intensity, temperature, and soil moisture on the growth of alfalfa, red clover, and birdsfoot trefoil seedlings. Agron. J. 49:33-36.

Hikosaka, K. and T. Hirose. 1997. Leaf angle as a strategy for light competition: Optimal and evolutionarily stable light-extinction coefficients within a leaf canopy. EcoScience 4:501-507.

Holland, J.B. and E.C. Brummer. 1999. Cultivar effects on oat-berseem intercrops. Agron. J. 91:321-329.

Keating, B.A. and P.S. Carberry. 1993. Resource capture and use in intercropping: Solar radiation. Field Crops Res. 34:273-301.

Klebesdal, L.J. and D. Smith. 1960. Effects of harvesting an oat companion crop at four stages of maturity on the yield of oats, on light near the soil surface, on soil moisture, and on the establishment of alfalfa. Agron. J. 52:627-630.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. Appl. 3:92-122.

Lin, C.Y. 1978. Index selection for genetic improvement of quantitative characters. Theor. Appl. Genet. 52:49-56.

Nickel, S.E., S.R. Simmons, C.C. Scheaffer, and S.R. Radosevich. 1990. Addition series approach to assessing competition in a small grain-alfalfa companion crop community. Crop Sci. 30:1139-1141.

Peters, R.A. 1960. Legume establishment as related to the presence or absence of an oat companion crop. Agron J. 52:195-198.

Pritchett, W.L. and L.B. Nelson. 1951. The effect of light intensity on the growth characteristics of alfalfa and bromegrass. Agron. J. 43:172-177.

Sakai, S. 1991. A model analysis for the adaptive architecture of herbaceous plants. J. Theoretical Biology 148:535-544.

Simmons, S.R., N.P. Martin, C.C. Scheaffer, D.D. Stuthman, E.L. Schiefelbein, and T. Haugen. 1992. Companion crop forage establishment: Producer practices and perceptions. J. Prod. Agric. 5:67-72.

Simmons, S.R., C.C. Scheaffer, D.C. Rasmusson, and S.E. Nickel. 1995. Alfalfa establishment with barley and oat companion crops differing in stature. Agron. J. 87:268-272.

Shipley, P.P., J.J. Meisinger, and A.M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agron. J. 84:869-876.

Skrdla, R.K. and J.-L. Jannink. 2002. Iowa Crop Performance Test – Winter Wheat, 1999-2002 and Winter Triticale, 2002. Iowa Crop Improvement Assoc., Ames, IA.

Skrdla, R.K. and J.-L. Jannink. 2003. Iowa Crop Performance Test – Winter Wheat, 2000-2003 and Winter Triticale, 2003. Iowa Crop Improvement Assoc., Ames, IA.

Tremmel, D.D. and F.A. Bazazz. 1993. How neighbor canopy architecture affects target plant performance. Ecology 74:2114-2124.

Tremmel, D.D. and F.A. Bazazz. 1995. Plant architecture and allocation in different neighborhoods: Implications for competitive success. Ecology 76:262-271.

Vandermeer, J. 1989. The Ecology of Intercropping. Cambridge Univ. Press, Cambridge, UK.

Welles, J.M. and J.M. Norman. 1991. Instrument for indirect measurement of canopy architecture. Agron. J. 83:818-825.

Tables

Table 1. Dates on which observations were conducted.

Variable	Date observed	
	2002	2003
April height	15 April	23 April
Early May height	9 May	15 May
Late May height	21 May	25 May
June height	6 June	18 June
May light interception	21 May	26 May
June light interception	6 June	18 June
May leaf area index	23 May	26 May
June leaf area index	10 June	24 June
May leaf angle	23 May	26 May
June leaf angle	10 June	24 June
Tiller density	10 June	3 June
Grain yield	5 July	17 July
Clover forage yield	20 August	3 September

Table 2. ANOVA statistics for effects of cereal grain line and year × line interaction on response variables.

		Wheat†			Triticale‡		
Variable	Source	MS§	F	p	MS	F	p
May light interception, %	line	48	1.6	0.13	34	1.5	0.20
	yr × line	30	1.5	0.10	22	1.4	0.18
	error	20			17		
June light interception, %	line	47	5.5	< 0.0001	22	2.5	0.035
	yr × line	8.7	1.1	0.32	8.9	1.4	0.18
	error	7.6			6.5		
May leaf area index	line	0.54	5.2	0.0001	0.45	4.1	0.0028
	yr × line	0.10	0.91	0.58	0.11	1.0	0.45
	error	0.11			0.11		
June leaf area index	line	0.72	7.6	< 0.0001	0.43	3.2	0.011
	yr × line	0.09	0.92	0.57	0.14	2.1	0.015
	error	0.10			0.06		
May leaf angle, °	line	18	2.2	0.028	11	2.5	0.03
	yr × line	8.2	1.3	0.20	4.4	1.2	0.31
	error	6.5			3.7		
June leaf angle, °	line	21	3.3	0.002	11	2.1	0.069
	yr × line	6.4	1.4	0.13	5.1	1.1	0.35
	error	4.6			4.6		
April height, cm	line	7.5	1.2	0.35	21.8	6.4	0.0002
	yr × line	6.4	2.5	0.008	3.4	1.4	0.17
	error	2.6			2.4		
Early May height, cm	line	58	2.2	0.028	94	4.8	0.0012
	yr × line	26	4.2	< 0.0001	20	2.6	0.0026
	error	6.3			7.5		
Late May height, cm	line	120	7.0	< 0.0001	280	7.2	0.0001
	yr × line	17	2.1	0.0053	39	3.7	0.0001
	error	8.2			11		
June height, cm	line	32	20	< 0.0001	320	7.8	< 0.0001
	yr × line	16	1.5	0.078	41	0.53	0.93
	error	10			76		
Tiller density, tillers m^{-1}	line	2200	2.5	0.015	540	2.3	0.050
	yr × line	890	1.2	0.27	240	0.53	0.93
	error	750			440		
Heading date, d.a. 1 May¶	line	21	28.0	< 0.001	26	11	< 0.0001
	yr × line	0.74	1.2	0.24	2.3	5.5	< 0.0001
	error	0.60			0.42		
Grain yield, Mg ha^{-1}	line	2000	1.8	0.075	3000	5.3	0.0006
	yr × line	1100	6.6	< 0.0001	560	1.8	0.051
	error	160			320		
Clover yield, Mg ha^{-1}	line	2.6	2.4	0.018	1.3	1.1	0.49
	yr × line	1.1	1.2	0.25	1.2	1.4	0.19
	error	0.88			0.92		

† df: line, 24; yr × line, 24; error, 96.
‡ df: line, 17; yr × line, 17; error, 68.
§ MS, mean squares.
¶ d.a., days after.

Table 3. Mean, min., max., and SD of response variables across years.

	Wheat				Triticale			
Variable	Mean	Min.	Max.	S.D.	Mean	Min.	Max.	SD
May light interception, %	91	82	95	3	92	87	96	2
June light interception, %	92	86	96	3	92	86	94	2
May leaf area index	3.9	3.2	4.2	0.3	3.7	3.0	4.1	0.3
June leaf area index	3.5	3.0	4.1	0.3	3.5	2.8	3.8	0.3
May leaf angle, °	30	34	27	1.7	31	33	28	1.4
June leaf angle, °	29	34	26	1.9	30	33	27	1.3
April height, cm	24	22	26	1	27	22	30	2
Early May height, cm	55	48	62	3	64	56	71	4
Late May height, cm	75	67	86	5	94	79	105	7
June height, cm	104	94	124	7	130	117	142	7
Tiller density, tillers m^{-1}	194	151	224	19	111	99	134	9
Heading date, d.a. 1 May†	28	24	32	1.9	25	22	29	2 .1
Grain yield, Mg ha^{-1}	6.1	5.2	7.1	0.6	6.5	4.6	7.7	0.7
Clover yield, Mg ha^{-1}	2.3	1.2	4.0	0.7	1.2	0.4	2.0	0.5

† d.a., days after.

Table 4. Pearson correlation coefficients between grain yield and clover forage yield and cereal grain response variables in wheat and triticale experiments across years.

	Wheat		Triticale	
Variable†	Grain yield	Clover yield	Grain yield	Clover yield
May LI	0.68***	-0.53**	0.37	-0.62**
June LI	0.59***	-0.47*	0.65**	-0.43
May LAI	0.47***	-0.59**	0.45	-0.66**
June LAI	0.65***	-0.46*	0.43	-0.43
May LA	0.27	-0.54**	0.43	-0.70***
June LA	0.45*	-0.33	0.37	-0.28
April height	0.24	-0.18	0.26	-0.39
E. May height	0.16	-0.24	0.18	-0.25
L. May height	0.23	-0.33	0.23	-0.39
June height	0.27	-0.37	0.23	-0.50*
Tiller density	0.12	0.05	0.08	0.23
Heading date	0.26	-0.22	-0.60**	0.04

*, **, *** Correlation significantly different from zero at the 0.05, 0.01, and 0.001 probability levels, respectively.

† LI, light interception; LAI, leaf area index; LA, leaf angle; e., early; l., late.

Table 5. Pairwise Pearson correlation coefficients between cereal grain response variables and clover forage yield in wheat (above diagonal) and triticale (below diagonal) experiments.

Variable†	May LI	June LI	May LAI	June LAI	May LA	June LA	April height	E. May height	L. May height	June height	Tiller density	Heading date	Grain yield	Clover yield
May LI		0.78***	0.82***	0.82***	0.65***	0.62***	0.39*	0.08	0.15	0.45*	0.32	0.40*	0.68***	-0.53**
June LI	0.67**		0.69***	0.85***	0.62***	0.75***	0.23	-0.14	-0.04	0.47*	0.45*	0.58**	0.59**	-0.47*
May LAI	0.78***	0.73***		0.78***	0.85***	0.60***	0.36	-0.19	-0.10	0.28	0.30	0.51**	0.47*	-0.59**
June LAI	0.59**	0.87***	0.84***		0.63***	0.84***	0.21	-0.27	-0.14	0.30	0.35	0.66***	0.65***	-0.46*
May LA	0.71***	0.50*	0.83***	0.56*		0.61***	0.43*	-0.23	-0.17	0.19	0.16	0.37	0.27	-0.54**
June LA	0.37	0.63**	0.52*	0.60**	0.46*		0.24	-0.23	-0.04	0.38	0.21	0.54	0.45*	-0.33
April height	0.53*	0.19	0.39	0.07	0.41	0.13		0.21	0.19	0.21	0.10	-0.13	0.24	-0.18
E. May height	0.53*	0.09	0.19	-0.14	0.32	0.08	0.63**		0.90***	0.43*	-0.22	-0.51**	0.16	-0.24
L. May height	0.62**	0.19	0.34	0.03	0.51*	0.29	0.55*	0.89***		0.62***	-0.23	-0.38	0.23	-0.33
June height	0.77***	0.50*	0.66**	0.48*	0.60**	0.35	0.43	0.57*	0.68***		0.08	0.22	0.27	-0.37
Tiller density	-0.07	-0.16	0.03	-0.03	-0.10	-0.37	-0.08	-0.11	-0.20	-0.27		0.22	0.12	0.05
Heading date	-0.22	-0.12	-0.03	0.15	-0.24	-0.26	-0.49*	-0.56*	-0.60**	-0.20	0.03		0.26	-0.22
Grain yield	0.37	0.65**	0.45	0.43	0.43	0.37	0.26	0.18	0.23	0.23	0.08	-0.60**		-0.43*
Clover yield	-0.62**	-0.43	-0.66**	-0.43	-0.70***	-0.28	-0.39	-0.25	-0.39	-0.50*	0.23	0.04	-0.29	

*, **, *** Correlation significantly different from zero at the 0.05, 0.01, and 0.001 probability levels, respectively.

† LI, light interception; LAI, leaf area index; LA, leaf angle; E., early; L., late.

CHAPTER 3. GENERAL CONCLUSIONS

Assessment of Cereal Grain Cultivars for Intercrop Performance and Yield Tradeoffs

Tradeoffs appeared to be present between grain and forage legume component yields in intercrops of winter wheat and red clover, and weaker evidence suggested the same relationship in the case of winter triticale. This result is broadly in concurrence with those of other researchers. Among the light competition-related variables surveyed, the pattern of tradeoffs seemed to continue, with those variables that demonstrably predicted both component yields differing in the sign associated with that prediction. The currently-available winter cereal grain cultivars surveyed did not readily grade into categories of greater or lesser suitability for intercropping, and farmers will likely need to base their choice of cultivars on the respective priorities they place on the component yields. Extension efforts may play a positive role in helping set those priorities. No readily apparent strategies for breeding efforts to avoid the component yield tradeoffs imposed by winter cereal grain cultivars were revealed.

Directions for Future Research

Costa and colleagues observed a striking biomass-accumulation pattern among 25 winter wheat cultivars entered in a 2000 study: early-season wheat biomass yield was correlated with neither late-season biomass yield nor grain yield. The present study provides reason to believe that mid-season light interception associated with high-yielding wheat cultivars plays a role in suppression of intercropped forage legume yields. If the biomass patterns observed by Costa et al. translate into similar light interception patterns, then the lack of an observed tradeoff between slow initial biomass accumulation and high final yields may create a window for avoidance of tradeoffs between components in winter wheat-forage legume intercrops. Royo and Blanco (1999) reported varying patterns of biomass accumulation among winter triticale cultivars that are less obviously favorable, but that suggest the possible presence of tractable variability for the same trait in that species. These pools of winter cereal grain genotypes may hold potential for tradeoff mitigation that the genotypes in the present study do not.

References

Costa, J.M., G.A. Bollero, and F.J. Coale. 2000. Early season nitrogen accumulation in winter wheat. J. Plant Nutr. 23:773-783.

Royo, C. and R. Blanco. 1999. Growth analysis of five spring and five winter triticale genotypes. Agron. J. 91:305-311.

ACKNOWLEDGMENTS

For a successful ending to the process culminating in this thesis I foremost thank my wife Melissa Calvillo. Her moral support, writing advice, and crisis fieldwork help made it possible for "our" M.S. program of study to proceed.

That process was also facilitated at every step by my co-major professors Dr. Charlie Brummer and Dr. Jean-Luc Jannink, Iowa State University (ISU) Department of Agronomy. What skills I have as a researcher and as an agronomist I owe in large part to them, and to their nearly inexhaustible stores of patience.

Feedback from POS Committee-member Dr. Jeremy Singer, USDA-ARS National Soil Tilth Laboratory, was constructive and insightful, and his determination to conduct my thesis defense in the face of personal injury was much appreciated. Dr. Rick Exner, Practical Farmers of Iowa, Dr. Ricardo Salvador, ISU Agronomy, and Dr. Win Phippen, Western Illinois University Department of Agriculture provided valuable advice on content and process; Dr. Exner and Dr. Phippen also provided generous accommodation as supervisors. I benefited greatly from interactions with numerous individuals in the ISU Graduate Program in Sustainable Agriculture, the Brummer and Jannink labs in ISU Agronomy, and The Land Institute and its Natural Systems Agriculture Fellows program.

Thanks to Dr. Steve Baenziger, University of Nebraska-Lincoln Department of Agronomy and Horticulture, for supplying the triticale breeding lines used, and to Dr. Ken Moore and Dr. Matt Liebman, ISU Department of Agronomy, for the use of field apparatus. Funding from The Land Institute and the ISU Raymond F. Baker Center for Plant Breeding is gratefully acknowledged.

APPENDIX. ADDITIONAL TABLES

Table A-1. Grain yields and forage yields of undersown red clover forage for wheat cultivars across years.

Cultivar	Type†	Grain yield	Clover yield
		—— Mg ha^{-1}	——
2137‡	HR	6.4	2.3
2145‡	HR	6.9	2.1
Arapahoe‡	HR	5.8	2.3
Cardinal‡	SR	6.3	1.8
Culver‡	HR	6.2	2.2
Custer‡	HR	6.7	1.7
Ernie‡	SR	5.3	4.0
Goldfield‡	SR	5.7	2.2
Heyne‡	HW	5.3	3.5
Howell‡	SR	5.7	3.4
Jagger‡	HR	5.5	2.8
Karl 92‡	HR	6.0	2.2
Kaskaskia‡	SR	7.1	1.6
Millennium‡	HR	6.9	2.9
NE97465	HR	6.4	1.3
NE97638	HR	6.4	1.9
NE97669	HR	5.9	1.2
NE97689	HR	6.8	1.6
Nekota‡	HR	5.6	2.2
Nuplains‡	HW	5.6	2
Patterson‡	SR	5.6	2.1
Siouxland‡	HR	5.2	1.9
Wahoo‡	HR	6.1	2.1
Wesley‡	HR	6.7	2.2
Winstar‡	HR	6.3	2.7
LSD(0.05)		NS	1.1

† HR, hard red; SR, soft red, HW, hard winter.
‡ Commercially available cultivar.

Table A-2. Grain yields and forage yields of undersown red clover forage for triticale genotypes across years.

Genotype	Grain yield	Clover yield
	—— Mg ha^{-1} ——	
Alzo†	6.2	1.6
Bobcat†	4.6	1.3
Décor†	6.4	2.0
NE95T426†	7.5	0.4
NE95T427	7.7	1.2
NE98T424	7.2	0.5
NE98T425	7.0	0.4
NE99T440	6.5	1.3
NE99T441	6.2	1.2
NE99T448	5.9	0.5
Newcale†	6.7	1.1
NT00418	6.6	1.6
NT00419	6.7	1.2
NT00421	5.8	1.2
NT00428	7.1	1.3
NT00449	6.2	1.3
Trical 336†	6.4	1.6
Trical 815†	6.4	1.7
LSD(0.05)	1.2	NS

† Commercially available cultivar.

Table A-3. Mean values of winter wheat lines on all response variables, averaged over years.

Line	Variable†													
	May LI	June LI	May LAI	June LAI	May LA	June LA	April height	E. May height	L. May height	June height	Tiller density	Heading date	Grain yield	Clover yield
	— % —				— ° —		— cm —				tillers m^{-1}	d.a. 1 May‡	— Mg ha^{-1} —	
2137	92	95	3.5	3.5	29	28	23	55	73	104	211	27	6.4	2.3
2145	92	93	4.1	3.5	31	28	26	53	72	97	207	28	6.9	2.1
Arapahoe	87	86	3.4	3.1	27	27	23	57	78	101	161	26	5.8	2.3
Cardinal	93	94	4.1	3.6	32	29	24	55	76	105	151	29	6.3	1.8
Culver	93	94	4.0	3.6	30	29	24	57	75	108	202	28	6.2	2.2
Custer	92	93	3.9	3.4	28	29	24	58	78	103	173	25	6.7	1.7
Ernie	89	87	3.6	3.0	28	27	24	54	72	96	191	26	5.3	4.0
Goldfield	90	88	3.8	3.1	30	28	22	57	79	101	168	26	5.7	2.2
Heyne	82	89	3.2	3.0	28	28	23	51	69	95	165	28	5.3	3.5
Howell	88	91	3.3	3.2	27	28	22	54	73	97	189	29	5.7	3.4
Jagger	89	90	3.6	3.2	29	29	25	57	77	99	209	24	5.5	2.8
Karl 92	90	92	3.9	3.4	31	30	24	53	76	102	206	25	6.0	2.2
Kaskaskia	93	92	4.0	3.6	29	29	23	62	85	111	190	28	7.1	1.6
Millennium	95	96	4.2	4.1	31	31	24	53	75	114	208	30	6.9	2.9
NE97465	93	95	3.9	3.6	30	31	25	59	86	124	194	29	6.4	1.3
NE97638	94	95	4.1	4.1	30	33	23	52	74	110	184	29	6.4	1.9
NE97669	91	93	4.2	3.7	32	29	23	52	68	97	190	30	5.9	1.2
NE97689	94	96	4.0	4.1	32	32	24	54	73	101	199	29	6.8	1.6
Nekota	92	93	4.1	3.5	30	29	24	55	74	103	223	28	5.6	2.2
Nuplains	92	94	4.2	3.7	31	30	22	58	67	98	222	32	5.6	2
Patterson	89	91	3.5	3.1	28	26	24	60	81	102	189	25	5.6	2.1
Siouxland	90	92	3.9	3.2	31	28	25	56	76	115	186	28	5.2	1.9
Wahoo	94	96	4.2	3.8	34	34	26	57	75	111	204	29	6.1	2.1
Wesley	95	94	4.2	4.0	31	31	26	52	72	94	197	29	6.7	2.2
Winstar	90	94	3.8	3.5	28	29	23	54	74	107	224	29	6.3	2.7

† LI, light interception; LAI, leaf area index; LA, leaf angle; E., early; L., late.
‡ d.a., days after.

Table A-4. Mean values of winter triticale lines on all response variables, averaged over years.

Line	May LI	June LI	May LAI	June LAI	May LA	June LA	April height	E. May height	L. May height	June height	Tiller density	Heading date	Grain yield	Clover yield
	Variable†													
	—— % ——				—— ° ——		—— cm ——				tillers m^{-1}	d.a. 1 May‡	— Mg ha^{-1} —	
Alzo	90	92	3.7	3.7	30	30	22	56	79	119	130	29	6.2	1.6
Bobcat	88	86	3.1	2.8	29	27	26	64	92	120	108	28	4.6	1.3
Décor	87	91	3.0	3.0	28	31	24	61	90	117	99	23	6.4	2.0
NE95T426	93	94	3.7	3.5	31	29	26	66	95	132	111	24	7.5	0.4
NE95T427	93	94	3.8	3.6	31	31	28	68	97	132	107	24	7.7	1.2
NE98T424	95	94	4.0	3.8	32	32	29	62	94	129	106	25	7.2	0.5
NE98T425	92	93	4.1	3.7	32	32	27	63	97	137	107	24	7.0	0.4
NE99T440	94	93	3.9	3.7	33	33	26	67	104	139	111	23	6.5	1.3
NE99T441	92	93	3.9	3.7	31	30	27	65	97	135	111	28	6.2	1.2
NE99T448	96	94	4.0	3.7	33	31	28	64	96	133	104	27	5.9	0.5
Newcale	93	90	3.8	3.2	32	30	30	71	105	131	121	22	6.7	1.1
NT00418	92	91	3.5	3.3	29	28	27	63	93	128	134	24	6.6	1.6
NT00419	93	91	3.7	3.2	32	29	28	68	100	131	116	23	6.7	1.2
NT00421	94	92	3.7	3.5	31	30	27	64	93	142	101	27	5.8	1.2
NT00428	93	92	3.8	3.5	32	29	26	65	94	131	108	24	7.1	1.3
NT00449	94	94	3.7	3.6	29	31	28	70	103	141	102	24	6.2	1.3
Trical 336	90	92	3.6	3.5	30	30	29	62	84	124	115	25	6.4	1.6
Trical 815	89	91	3.5	3.5	30	29	25	56	85	125	106	26	6.4	1.7

† LI, light interception; LAI, leaf area index; LA, leaf angle; E., early; L., late.
‡ d.a., days after.